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NINTH INTERIM TECHNICAL PROGRESS REPORT

TO

MANUFACTURING TECHNOLOGY DIVISION

AF MATERIALS LABORATORY

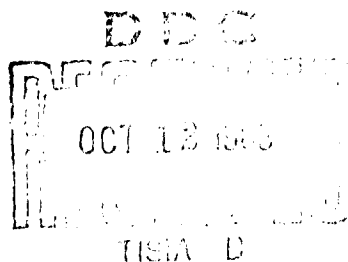
AFSC AERONAUTICAL SYSTEMS DIVISION

TUNGSTEN FORGING

DEVELOPMENT PROGRAM

CONTRACT No. AF 33(600)41629

19 AUGUST 1963



MATERIALS PROCESSING DEPARTMENT

TAPCO

A DIVISION OF

Thompson Ramo Wooldridge Inc.

CLEVELAND 17, OHIO



ASD TR 7-797 (IX)

ASD INTERIM REPORT 7-797 (IX)
August 1963

TUNGSTEN FORGING DEVELOPMENT PROGRAM

E. J. Breznyak

Materials Processing Department
TAPCO a division of
THOMPSON RAMO WOOLDRIDGE INC.
Contract: AF 33(600)-41629
ASD Project: 7-797

ASD Project Engineer: L. C. Polley

Ninth Interim Technical Progress Report
19 May 1963 - 19 August 1963

The forging process developed for the Phase V universal thin section W-2%Mo forging has been successfully scaled up. Initial forging trials of the scaled up configuration have been completed with high purity cast extruded unalloyed tungsten billets having hot-cold worked and recrystallized structures. Test data indicate the superiority of starting billets of uniformly recrystallized structures. Evaluation of forgings produced demonstrates that forging quality can be controlled during scale up. Ductile-brittle transition temperature and high temperature tensile properties are reported.

MANUFACTURING TECHNOLOGY DIVISION
Air Force Materials Laboratory
AFSC Aeronautical Systems Division
United States Air Force
Wright-Patterson Air Force Base, Ohio



ABSTRACT - SUMMARY

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Initial forging trials of the scaled up configuration have been completed. The starting billets were high purity cast-extruded unalloyed tungsten billets having hot-cold worked and recrystallized structures. Analysis of forgeability and property data indicate the superiority of starting billets of uniformly recrystallized starting structures. Evaluation of unalloyed tungsten thin section forgings produced demonstrates that superior surface finish, dimensional tolerances, and soundness can be controlled during scale up.

Ductile-brittle transition temperature and 3000°F, 3500°F, 4000°F, and 5000°F tensile properties of the unalloyed tungsten forgings are reported.



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FOREWORD

This Interim Technical Progress Report covers the work performed under Contract AF 33(600)-41629 from 19 May 1963 to 19 August 1963. It is published for technical information only and does not necessarily represent the recommendations, conclusions, or approval of the Air Force.

This contract with the Materials Technology of TAPCO a division of Thompson Ramo Wooldridge Inc., Cleveland, Ohio was initiated under ASD Project 7-797, "Tungsten Forging Development". It is administered under the direction of Mr. L. C. Polley of the Manufacturing Technology Division, Air Force Materials Laboratory, AFSC Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio.

E. J. Breznyak of the Materials Processing Department, TAPCO a division of Thompson Ramo Wooldridge was the Engineer in charge.

PUBLICATION REVIEW

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I INTRODUCTION

The use of tungsten for ultrahigh temperature components in aerospace vehicles is still a relatively new concept. Only since projected operating temperatures have reached 3000°F and above has the density of tungsten been viewed as anything but undesirable. The success of rocket nozzle engineers in designing around tungsten's density has further prompted a re-evaluation of the applicability of tungsten as a material for load carrying structural components.

The basic manufacturing method for aerospace structural components is forging. For tungsten, however, forging methods did not exist except as related to conversion steps in the lamp industry and as used for preliminary rocket nozzle shaping. For this reason the Aeronautical Systems Division, Manufacturing Technology Laboratory, initiated the present program with Thompson Ramo Wooldridge for the development of forging methods for tungsten and its alloys.

The principal objective of the program was the development of methods for producing tungsten forgings for structural use in aerospace vehicles. To accomplish this aim the program was originally divided into five phases consistent with the state-of-the-art and with the non-integrated nature of the refractory metal and forging industries. The objectives of each of these original five phases are summarized below:

Phase I State-of-the-Art-Analysis

An evaluation of the tungsten and forging industry state-of-the-art in order to satisfactorily plan the program for subsequent phases. This was completed and reported in the First Interim Technical Progress Report on 31 August 1960.

Phase II Billet Process Development

The development of processes for the production and conversion of sound tungsten ingots to quality forging bar stock. This was completed and reported in the Second Interim Technical Progress Report on 12 December 1960.

Phase III Development of the Forging Operation

The forging of tungsten billets to establish forging process parameters, controls, and tests for the controlled forging of tungsten. This was completed and reported in the Third and Fourth Interim Technical Progress Reports on 27 March and 27 May 1961 respectively.



Phase IV Forging Process Verification and Post-Forging Development

Forging tungsten to verify the developed process and the subsequent development of applicable post-forging operations. This was completed and reported in the Fifth Interim Technical Progress Report on 9 November 1961.

Phase V Final Pilot Production

Pilot production to demonstrate reliability of the developed process and of the forgings produced. This phase was successfully completed with Phase IV and also reported in the Fifth Interim Technical Progress Report.

That all of the program objectives were met is well documented (1-5). In addition, the original objectives of Phases III, IV, and V; i.e., those of development and pilot production verification of controlled precision forging methods for structural tungsten components, were accomplished within the boundaries of the third and the fourth phases. For these reasons the program has been modified and extended for adaptation of the developed technique to the continuing and more immediate problem of thin section, nonstructural tungsten shapes currently required by the rocket engine industry. The specific objectives of the revised fifth phase and the additional sixth phase are:

Phase V Development of Thin Section Forging Process

Extension of the developed forging process to controlled precision forging of thin section, nonstructural tungsten shapes having optimum properties.

Phase VI Verification of Thin Section Forging Process

Production of scaled-up thin section forgings to verify and demonstrate applicability of the process.

This Ninth Interim Technical Progress Report details the initial scaled-up forging trials of the Phase VI program effort.



II PHASE VI PROGRAM

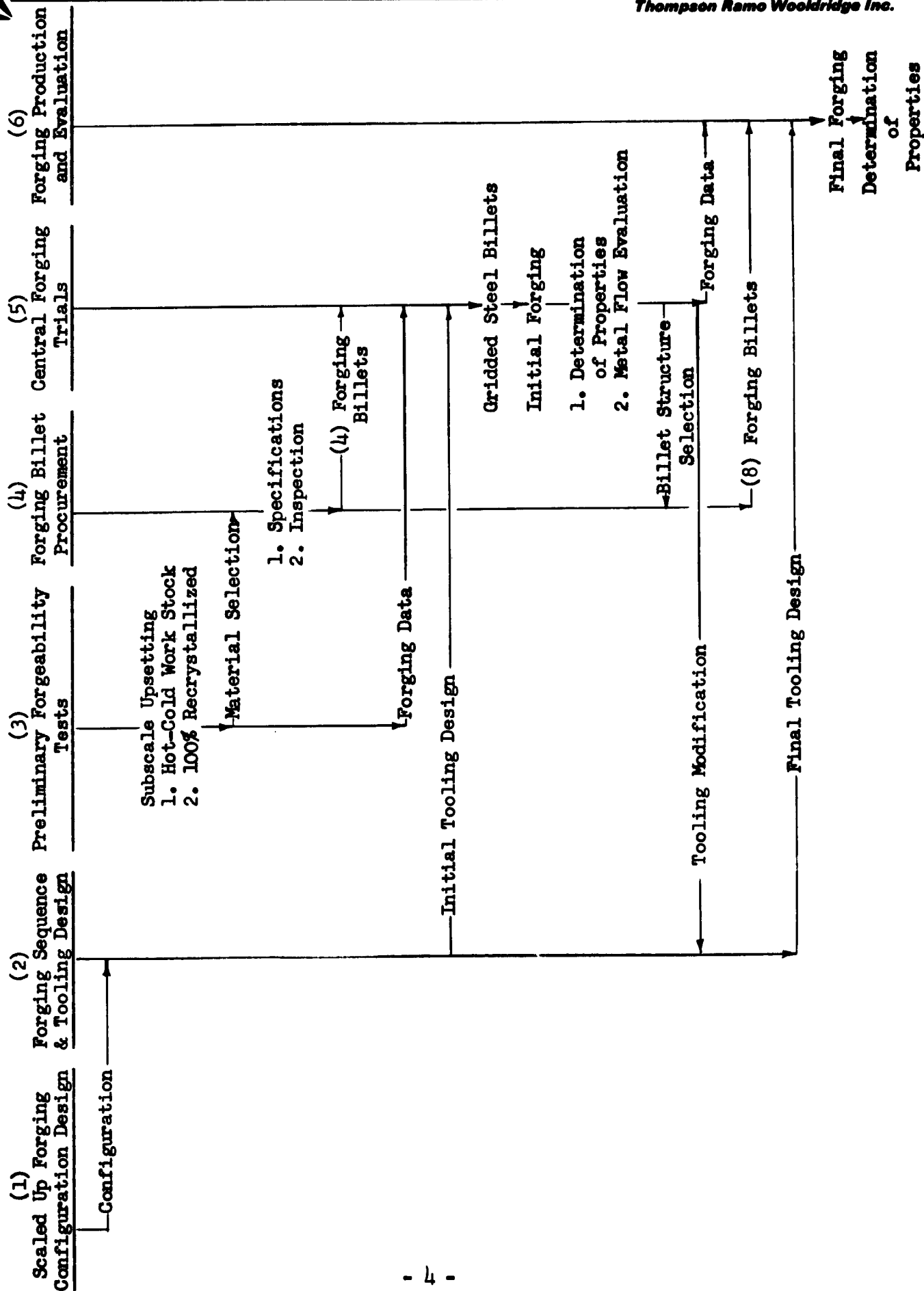
The objective of Phase V was adaptation of the process developed for structural forgings to thin section tungsten components presently required for aerospace applications. That the objective has been successfully achieved has been demonstrated^(6, 7), i.e., the evaluation of the close tolerance forging sequence developed showed dimensional reproducibility, excellent as-forged surfaces, and desirable grain flow orientation in the final thin section components. The Phase VI objective is to verify this thin section tungsten forging process, developed during Phase V, by scaling up to a larger specific thin section design. The principal criterion to be used for judging the universal applicability of the forging process is the extent to which the mechanical properties of the thin section forging can be controlled and maintained during scale-up. The tasks scheduled for accomplishing the Phase VI objectives are:

1. Design of a scaled-up configuration and tooling sequence compatible with both previous design and process data and the requirements of the aerospace industry for thin section tungsten components in the 50 to 70 pound range.
2. Selection and procurement of arc melted and extruded forging billets.
3. Development of the scaled-up forging process to provide optimum properties in the thin section component.
4. Property determination and evaluation of the scaled-up thin section tungsten component.

The organization of these interrelated tasks into the Phase VI program effort is illustrated schematically in Figure 1.



PHASE VI VERIFICATION OF THIN SECTION FORGING PROCESS





III FORGING BILLET PROCUREMENT

Four cast-extruded unalloyed tungsten billets were procured from Climax Molybdenum of Michigan for the initial Phase VI forging trials. The billets were conditioned from 8 in. diameter arc-cast ingots extruded at a reduction ratio of 3.5/1 within a temperature range of 3100-3150°F. Two forging billets with as-extruded and stress relieved hot-cold worked structures and two with fully recrystallized structures were selected for the initial forging effort. The selection of these starting structures was based upon results of upset forgeability tests and microstructure examinations of the extrusions from which it was concluded that:

1. Upsetting of stress relieved slugs resulted in a non-uniformly worked structure in comparison to the recrystallized and upset extrusion.
2. The grain size of the hot-cold worked grains was at least one order of magnitude larger than the recrystallized grains.

The billets ground at TAPCO to the designated forging billet size of 3.750 in. diameter by 6.500 in. length met the requirements of the billet quality control specification reported previously⁽⁸⁾. Prior to forging, the four billets were identified according to starting structure and their position within the extrusion, i.e., R-1 and R-2 refer to recrystallized billets sectioned from first and second positions starting from the lead end of the extrusion while S-2 and S-3 designate stress relieved billets etc.



IV DEVELOPMENT OF SCALED UP THIN SECTION DESIGN

A. Component, Sequence, and Tooling Design

The scaled up thin section configuration and the six stage sequence designed to produce the forging are shown in Figures 2 and 3. The forgings produced at each stage of the sequence are displayed in Figure 4.

The closed die sequence established the forging volume to fill each stage of the sequence at 72 in.³, (3-3/4 in. diameter by 6-1/3 in. long) as compared to the Phase V billet volume of 28.7 in.³, (2-3/4 in. diameter by 4-7/8 in. long).

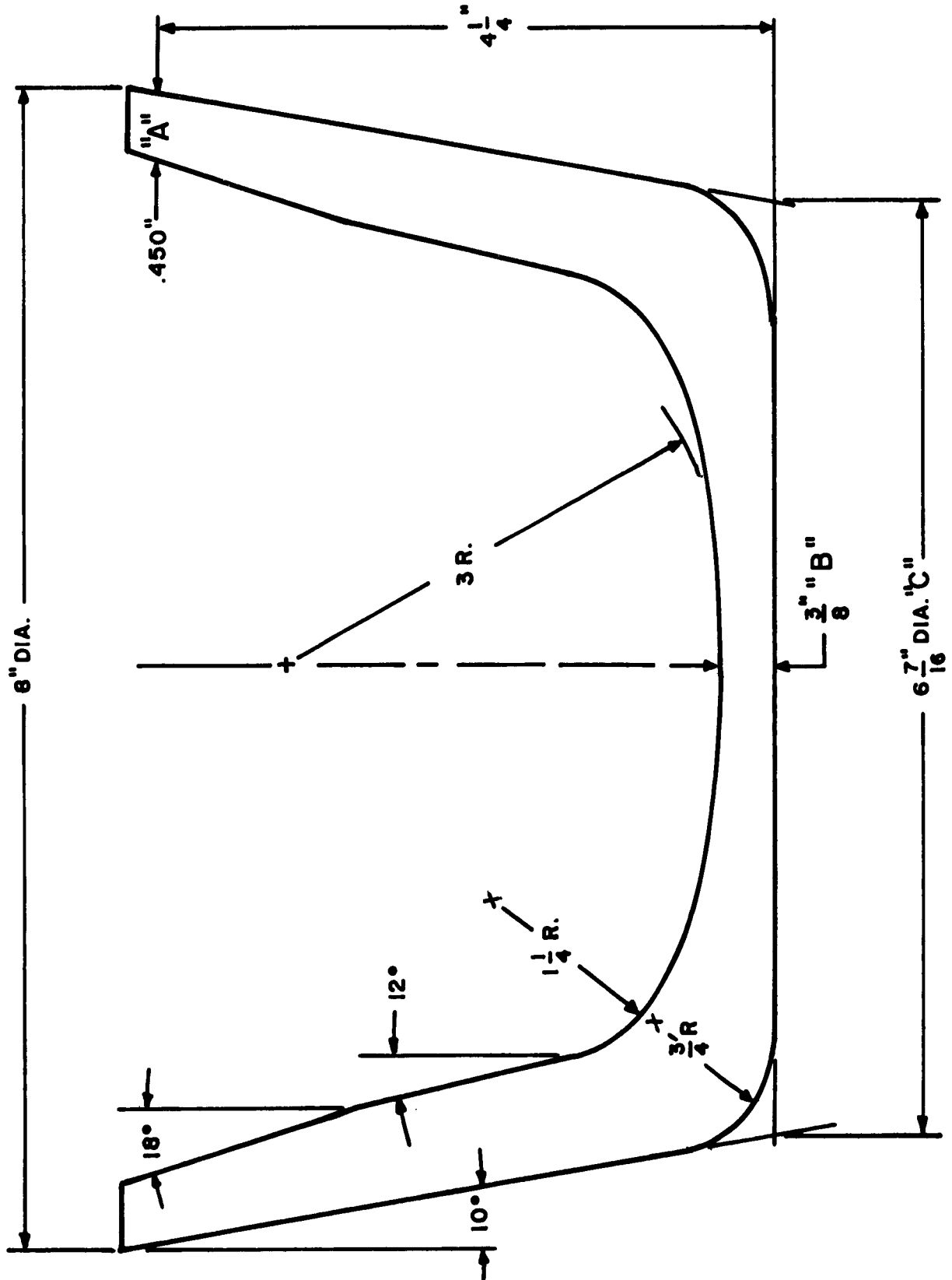
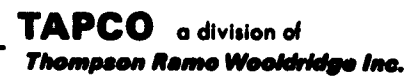
Because of the severe 70% upset requirement (see Figure 3) of the scaled up sequence, a third closed die upsetting operation was added to the forging sequence developed during Phase V. The die utilized for the third upsetting operation was the same die used during the subsequent three back extrusion operations.

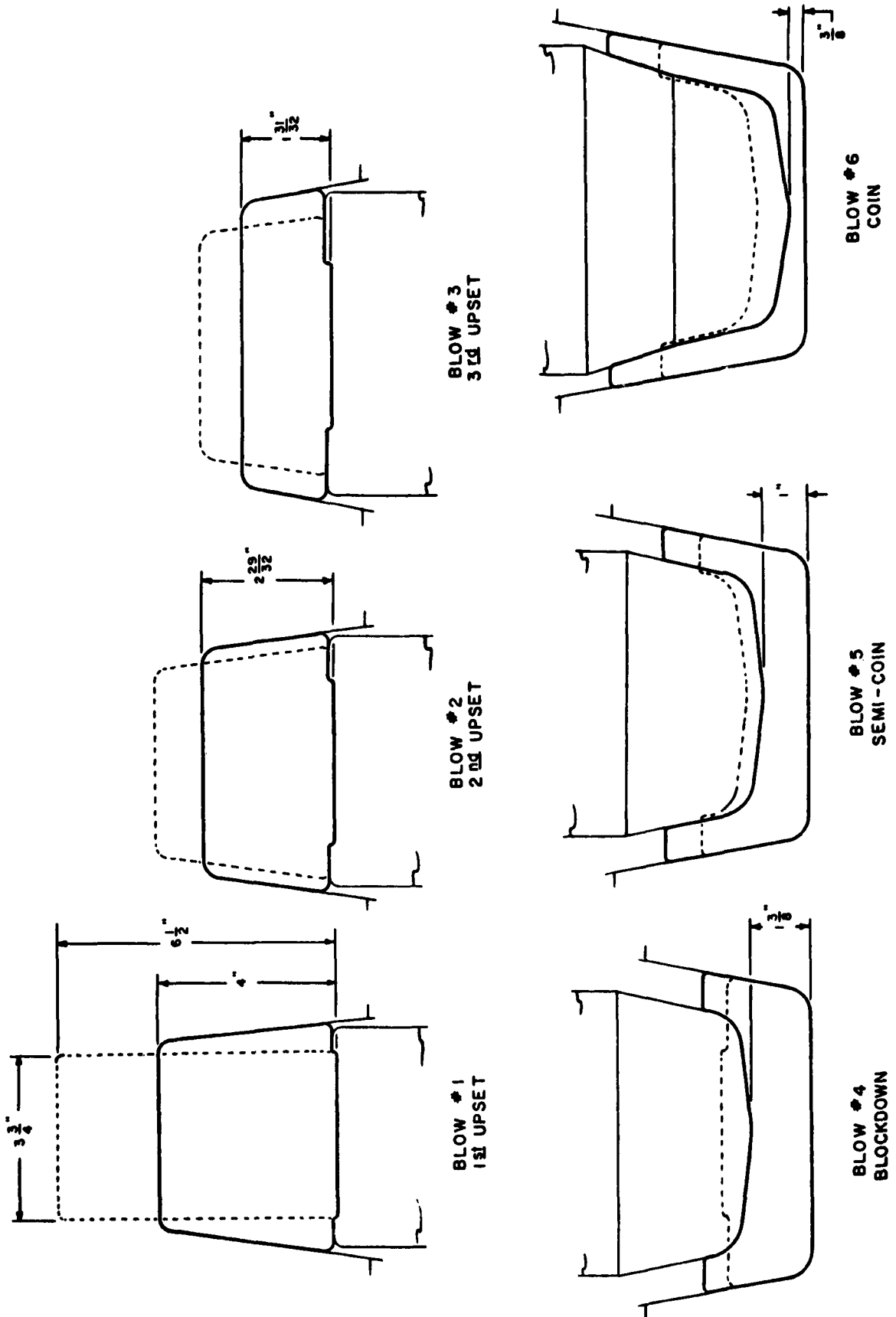
During the Phase V back extrusion operations, moderate surface tearing in the regions of the inner and outer cup radii were observed⁽⁷⁾. In an attempt to alleviate this surface tearing, larger radii on punch and die faces were incorporated into the scaled up design.

B. Heating and Forging Equipment

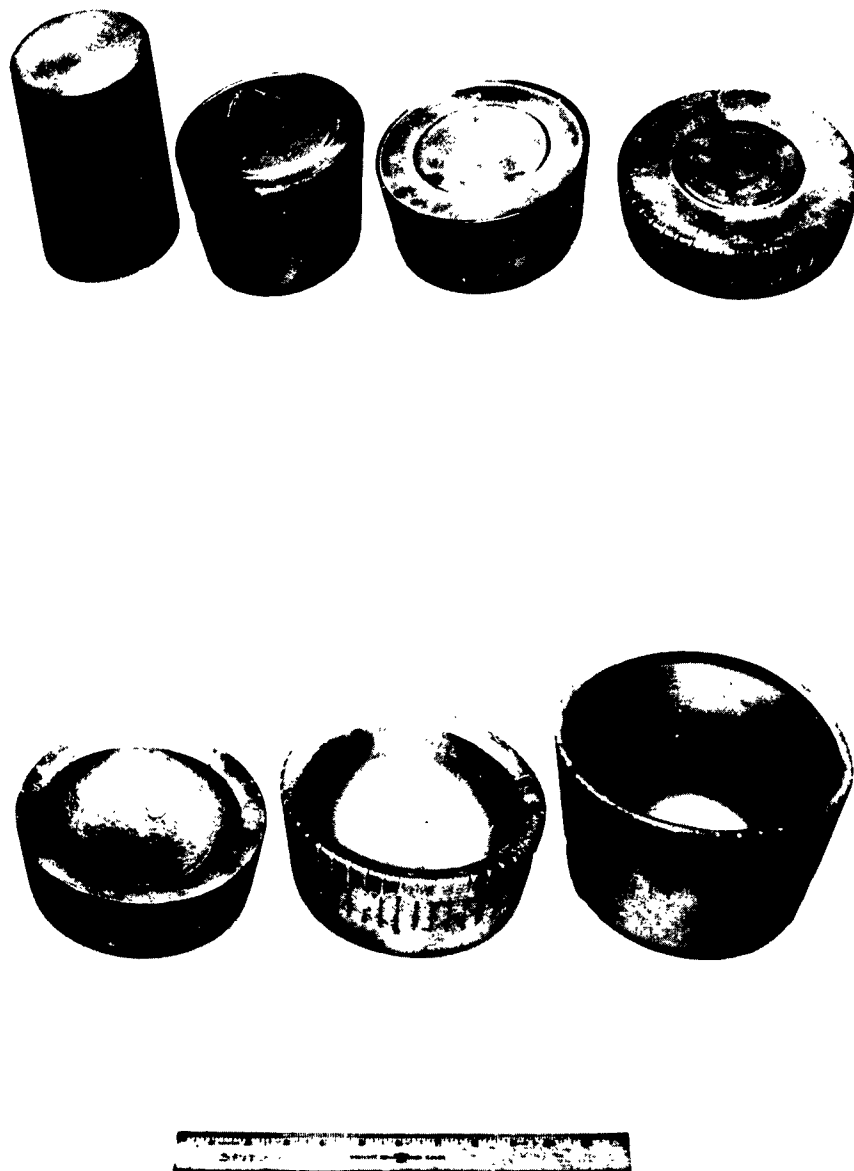
An electric furnace purged with argon was used for heating. Temperature measurements were made using an optical pyrometer shown to be within $\pm 20^\circ\text{F}$ of duplicate Chromel-Alumel thermocouple readings for the forging temperature range utilized (2200°F to 2350°F). A total billet heating time of 30 minutes, as previously established⁽⁷⁾, was used to reach forging temperatures. After the forging blow was struck at the predetermined forging temperature, the tungsten work pieces were returned for a 30 minute period to a second electric furnace at 2000°F for a temperature equalization. The work pieces were then buried in silocel allowing the forged configuration to uniformly slow cool from 2000°F through the ductile-brittle transition temperature.

Component size and pressure requirements necessitated the use of the 8000 ton mechanical crank press. The press utilizes a 20 in. stroke and is equipped with a vertical tooling adjustment with capability for maintaining a tolerance of ± 0.003 . The 8000 ton press and the heating facility used during the Phase VI forging trials are shown in Figure 5.

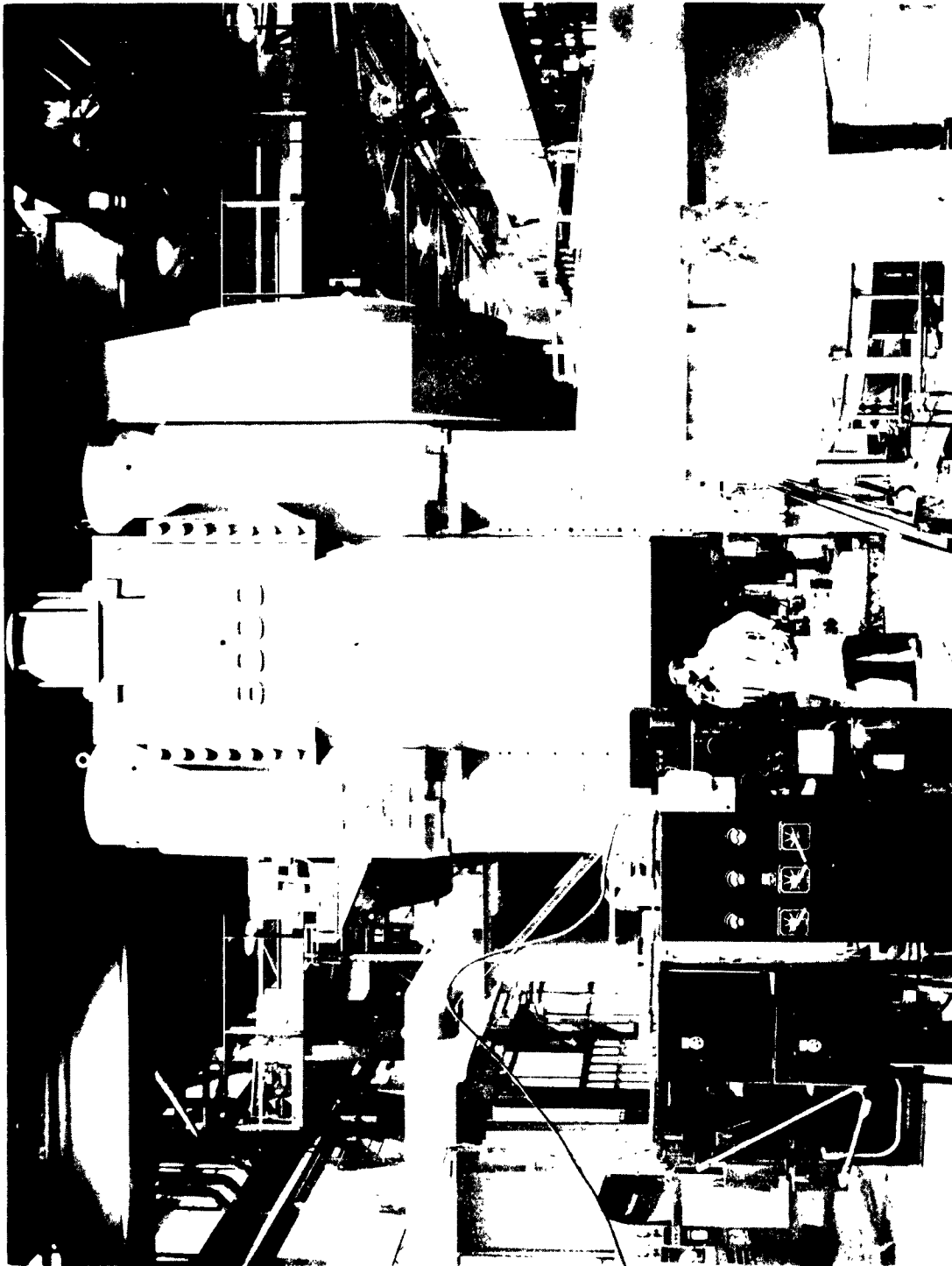




FORGING SEQUENCE FOR SCALED UP CONFIGURATION



Forging Configurations Produced through Six Step Forging
Sequence as Shown by Steel Set-Up Billets and Gridded
Steel Composite Billets



8000 Ton Mechanical Press and Heating Facility Used
During Phase VI Forging Trials



C. Forging Development

1. Sequence Metal Flow Evaluation

To aid in metal flow evaluation of the tooling sequence designed, three composite gridded steel billets were assembled, as previously detailed⁽⁷⁾, and forged at 1800°F. The billets were withheld as forged to the upset No. 3, semi-coin, and coin configurations as shown in Figure 6. These forgings were then sectioned and etched to show the mode of metal redistribution produced by the designed sequence, as shown in Figure 7. The severity of the sidewall metal movement during the coining blow is apparent. A review of the Phase V gridded sections⁽⁷⁾ reveals the similarities produced in the scaled up section, i.e.:

- a. The sidewall metal flow, although more severe, is uniform with flow lines parallel to the punch and sidewall.
- b. The cup bottom is formed by the center billet core while the cup sidewalls are formed by the elongated outer cylinders.
- c. Lapping or tearing tendencies of the work piece are not apparent at the tooling radii contact surfaces.

2. Tungsten Forging Trials

Four cast-extruded unalloyed tungsten forging billets, two of as-extruded and stress relieved hot-cold worked structures (Nos. S-2 and S-3) and two in a fully recrystallized condition (Nos. R-1 and R-2) comprised the starting stock for the tungsten forging trials. Low carbon steel stock machined to the starting billet size and the gridded composite steel billets provided the setup billets for preliminary tooling adjustments.

The punch and die inserts were preheated to a temperature range of approximately 350°F to 425°F. A thin coating of colloidal graphite lubricant was applied to the tooling surfaces prior to each blow. The tungsten billets were forged bare; the volatile surface oxide produced during heating provides lubrication. The optimum forging temperatures established during Phase V prompted the selection of the following temperatures for the scaled up six stage sequence:

Upset No. 1	2350°F
Upset No. 2	2300°F
Upset No. 3	2300°F
Blockdown	2250°F
Semi-Coin	2200°F
Coin	2200°F



(A) Upset No. 3 (B) Semi-Coin (C) Coin

0 1 2 3 INCHES

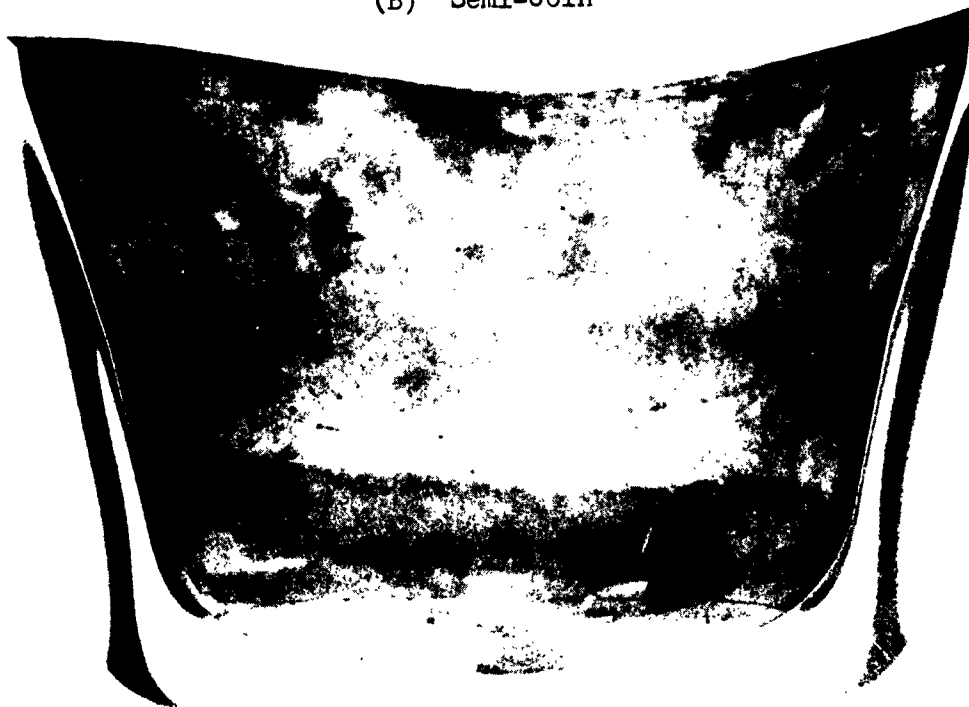
Gridded Composite Billets Forged to (A) Upset No. 3,
(B) Semi-Coin, and (C) Coin Configurations for Metal
Flow Evaluation



(A) Upset No. 3



(B) Semi-Coin



(C) Coin

.65X

Gridded Steel Composite Billets Sectioned at Forging
Stages Indicated



The tungsten billets were forged as outlined in Section IV-B. The forging data are listed in Table I. Post forging processing upon completion of each forging blow consisted of sand blasting followed by superzyglo fluorescent penetrant inspection of the forged surface. Surface irregularities were noted (see Table I), repaired manually with an air grinder, and re-examined by red dye penetrant inspection. A summary of the observations is as follows:

a. Recrystallized Starting Billet Stock

Billet Nos. R-1 and R-2 generally forged well throughout the sequence. Some sidewall roughness was exhibited after Upset No. 1. This surface irregularity, attributed to the unsupported lateral movement of the billet sidewall during the initial 38% upset, was readily repaired by grinding. During the subsequent forging stages, the surface appearance of the tungsten pieces progressively improved. The only surface conditioning required during the back extrusion operations was slight blending of surface tears in the inner and outer cup radii. The as-coined forged and sand blasted surface appearance of Nos. R-1 and R-2 are compared to Nos. S-2 and S-3 in Figures 8 and 9.

b. Hot-Cold Worked Billet Stock

The degree of in-process repairing required after each of the first four stages for billets S-2 and S-3 are noted in Table I. Billet S-2 cracked severely in the die flat and radius surface region during upset No. 2 (see Figure 8). The deep cracking was non-repairable and therefore No. S-2 was used as the tungsten set up billet for the subsequent forging stages. Since forging process parameters were constant, the rough surfaces, surface tears, and radial cracking observed for billets S-2 and S-3 through the first four stages can be, in part, related to non-uniform response to the forging deformation of the mixed grain sizes known to exist in the initial forging billets. The sidewall surface condition of Nos. S-2 and S-3 greatly improved during the semi-coin and coin operations, where complete work piece support was provided by the punch and die contours throughout the forging stroke. However, a comparison of the surface appearance, particularly in the outer cup radius and bottom surface of forgings S-3 and R-1 (Figure 9) show the surface superiority of the latter. Forging S-3, although requiring extensive conditioning between operations, resulted in a sound coined forging.

Coined forgings R-2 and S-2 were sectioned to evaluate the metal flow produced by the sequence and the effect of the starting microstructure on the final forged part. Center section macrostructures of these coined pieces are shown in Figures 10 and 11. A close comparison of these tungsten sections reveals no apparent differences in the macro



TABLE I
PHASE VI TUNGSTEN FORGING TRIALS

<u>Upset No. 1</u>					
<u>Billet No.</u>	<u>Forging⁽¹⁾ Temp. °F</u>	<u>Tooling Temp. °F</u>		<u>Upset Height In.</u>	<u>Condition of Forging</u>
		<u>Punch</u>	<u>Die</u>		
R-1 ⁽²⁾	2360	350	350	4.250	Top and bottom face smooth, slight tear near flash area, rough sidewall.
R-2	2370	400	400	4.248	Rough sidewall.
S-2	2370	350	370	4.260	Crack 1/4" on die side flat, sidewall very rough.
S-3	2380	340	400	4.265	Crack on sidewall 3/8" long by approximately 1/8" deep, very rough sidewall.
<u>Upset No. 2</u>					
R-1 ⁽²⁾	2320	400	400	3.060	Good surface appearance, sidewall needed only slight buffing touch up.
R-2	2320	380	350	3.062	Good surface appearance, sidewall needed only slight buffing touch up.
S-2	2330	390	400	3.071	Repaired area opened into a series of very severe cracks (non-repairable).
S-3	2330	380	370	3.070	Rough sidewall, surface tearing on flash flat face area.
<u>Upset No. 3</u>					
R-1	2310	420	380	2-1/4	Good appearance all over.
R-2	2320	350	370	2-1/4	Good appearance all over.
S-2 ⁽²⁾	2300	400	400	2-1/4	Rough sidewall, cracks on die face not propagating.
S-3	2320	370	400	2-1/4	Rough sidewall, slight crack in previously repaired area, repairable.
<u>Blockdown</u>					
R-1	2260	410	380	1.460	Good sidewall surface, needed blending in I.D. and O.D. radius.

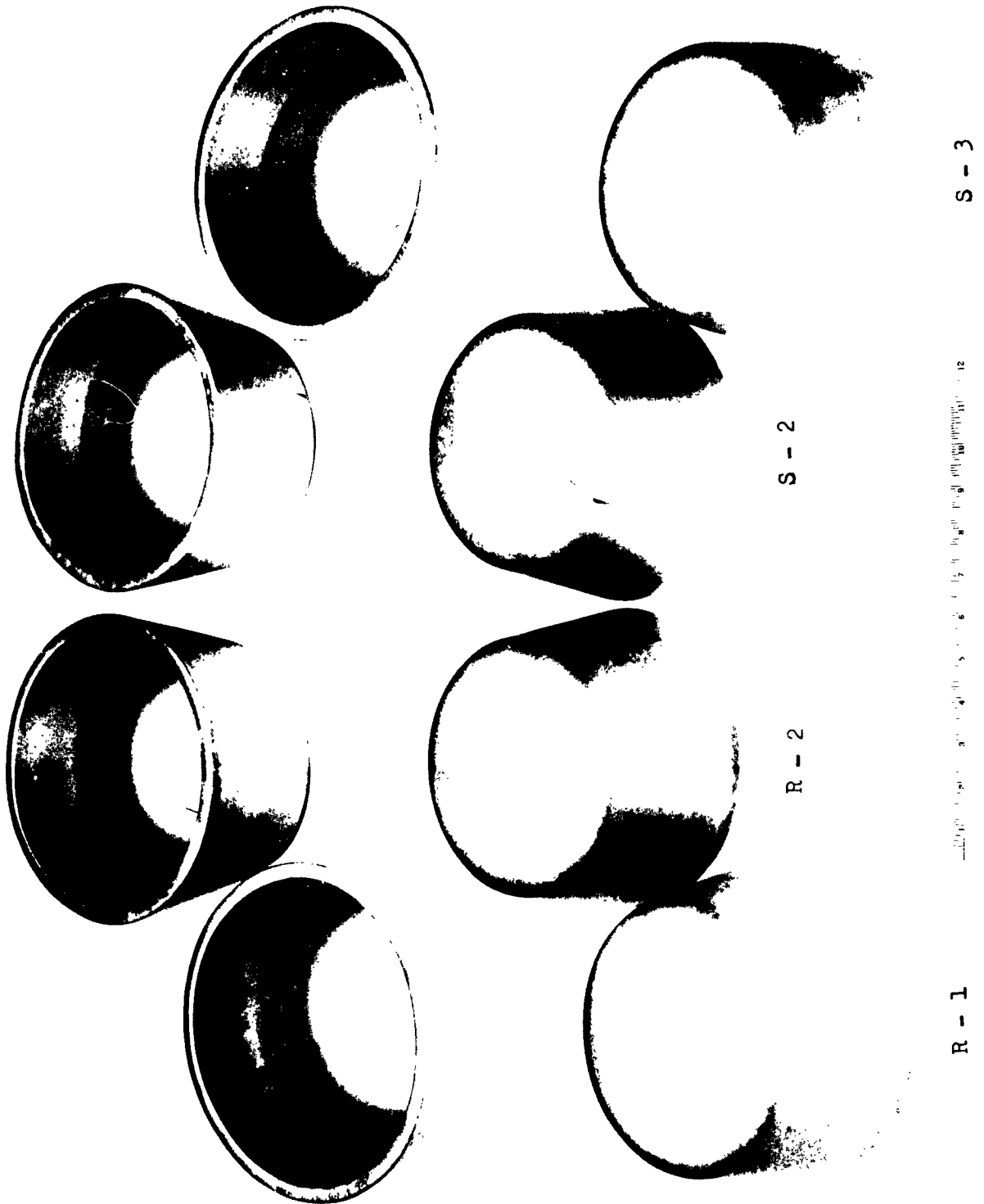


TABLE I (continued)

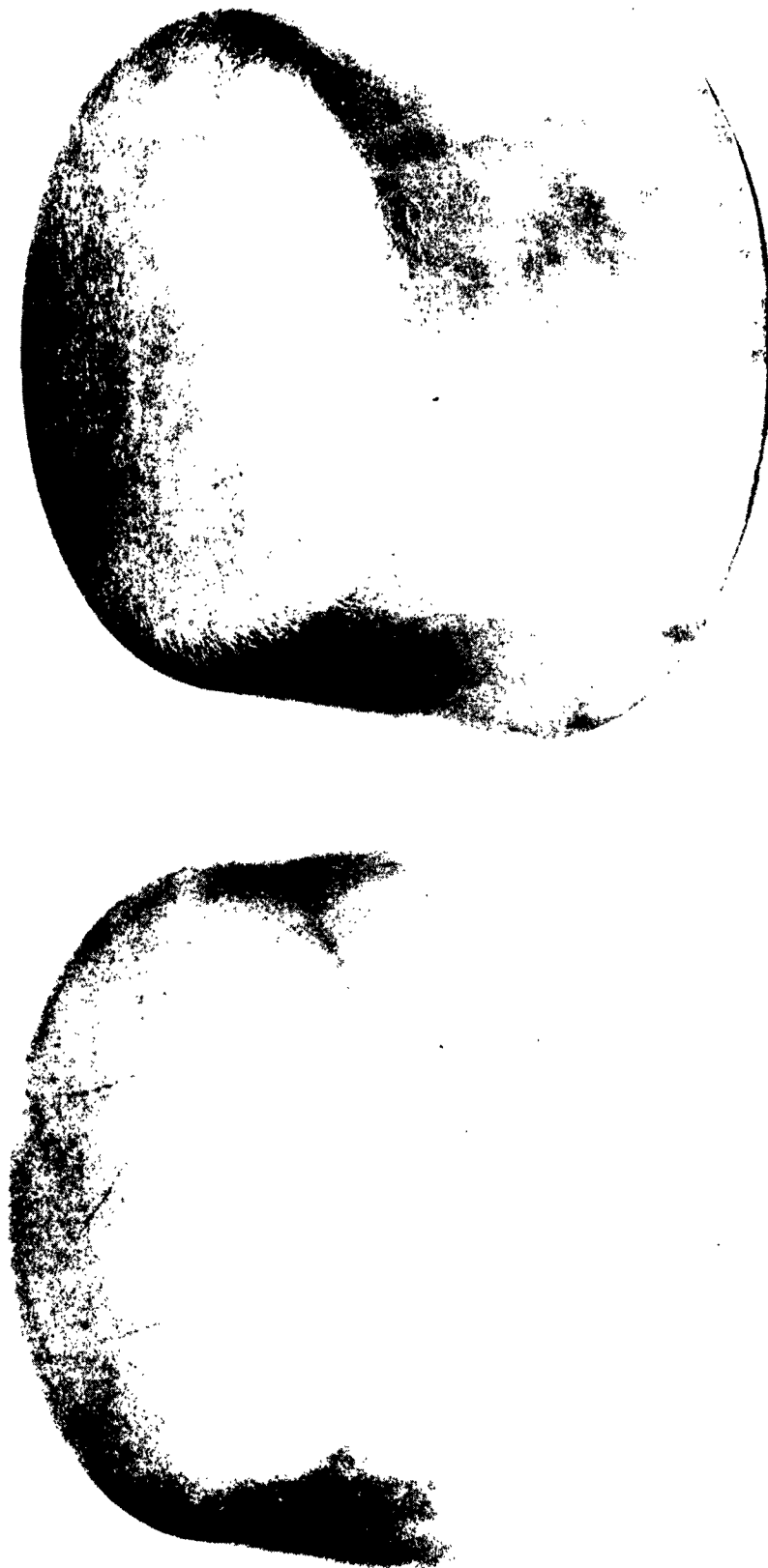
<u>Billet No.</u>	<u>Forging⁽¹⁾ Temp. °F</u>	<u>Tooling Temp. °F</u>		<u>Upset Height In.</u>	<u>Condition of Forging</u>
		<u>Punch</u>	<u>Die</u>		
<u>Blockdown (continued)</u>					
R-2	2250	380	370	1.450	Good sidewall surface, needed blending in I.D. and O.D. radius.
S-2 ⁽²⁾	2260	380	390	1.459	Required I.D. and O.D. Blend- ing, cracks not propagating.
S-3	2260	400	400	1.456	Good surface like R-1 and R-2, slight radial crack on O.D. radius about 1/4" long.
<u>Semi-Coin</u>					
R-1	2185	350	360	1.040	Surface condition excellent, only slightly rough areas in O.D. radius.
R-2	2220	370	370	1.050	Surface condition excellent, only slightly rough areas in O.D. radius.
S-2 ⁽²⁾	2205	350	400	1.065	Surface condition excellent, except for moderate surface tears in O.D. radius.
S-3	2220	360	400	1.055	Surface condition excellent, except for moderate surface tears in O.D. radius.
<u>Coin</u>					
R-1	2220	380	400	.325	See Figures 8 and 9.
R-2	2210	380	410	.335	See Figure 8.
S-2 ⁽²⁾	2205	370	380	.338	See Figures 8 and 9.
S-3	2220	380	400	.336	See Figure 8.

(1) Optical temperature determinations (see Section IV-B).

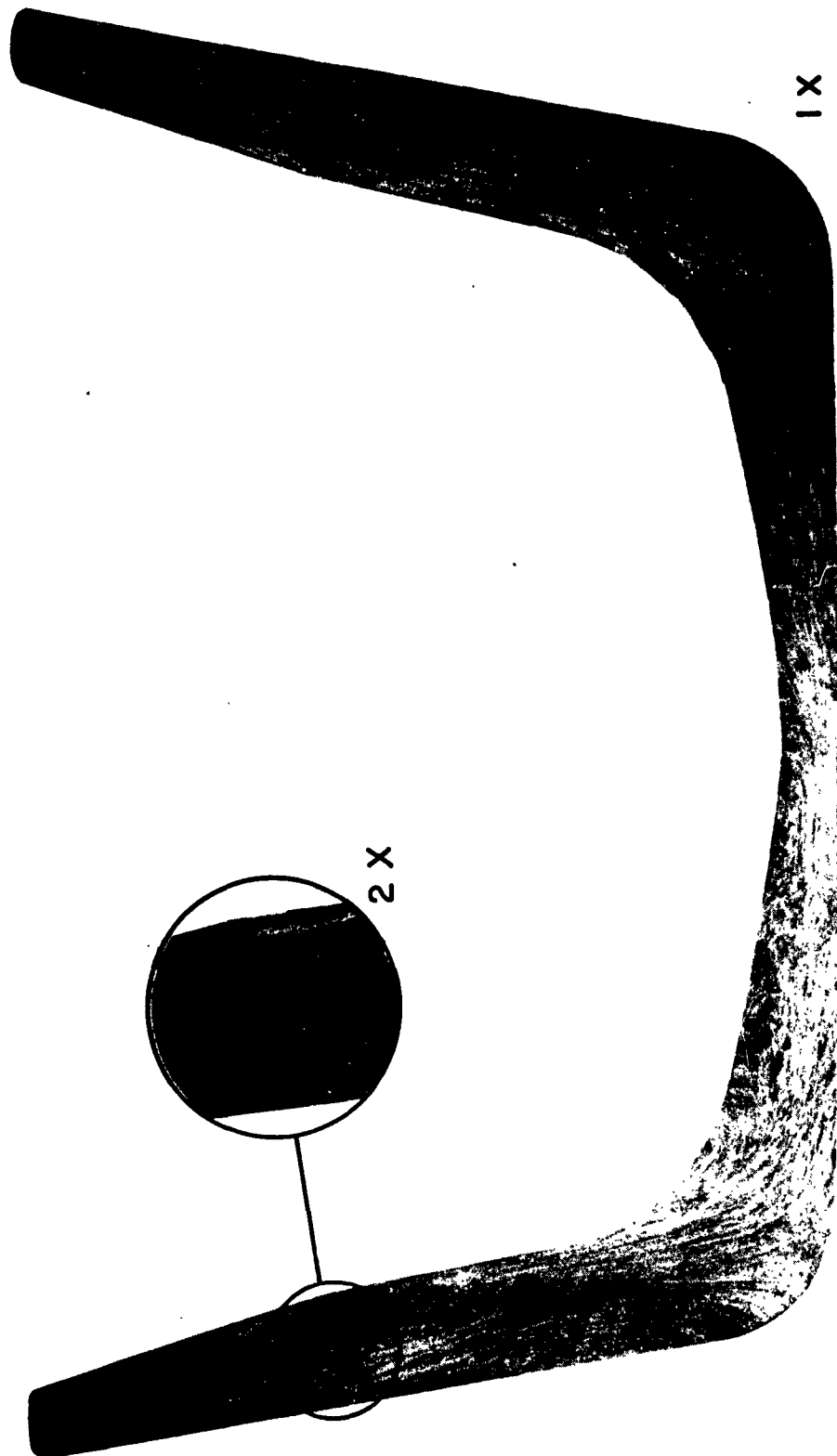
(2) Used as tungsten set-up piece.



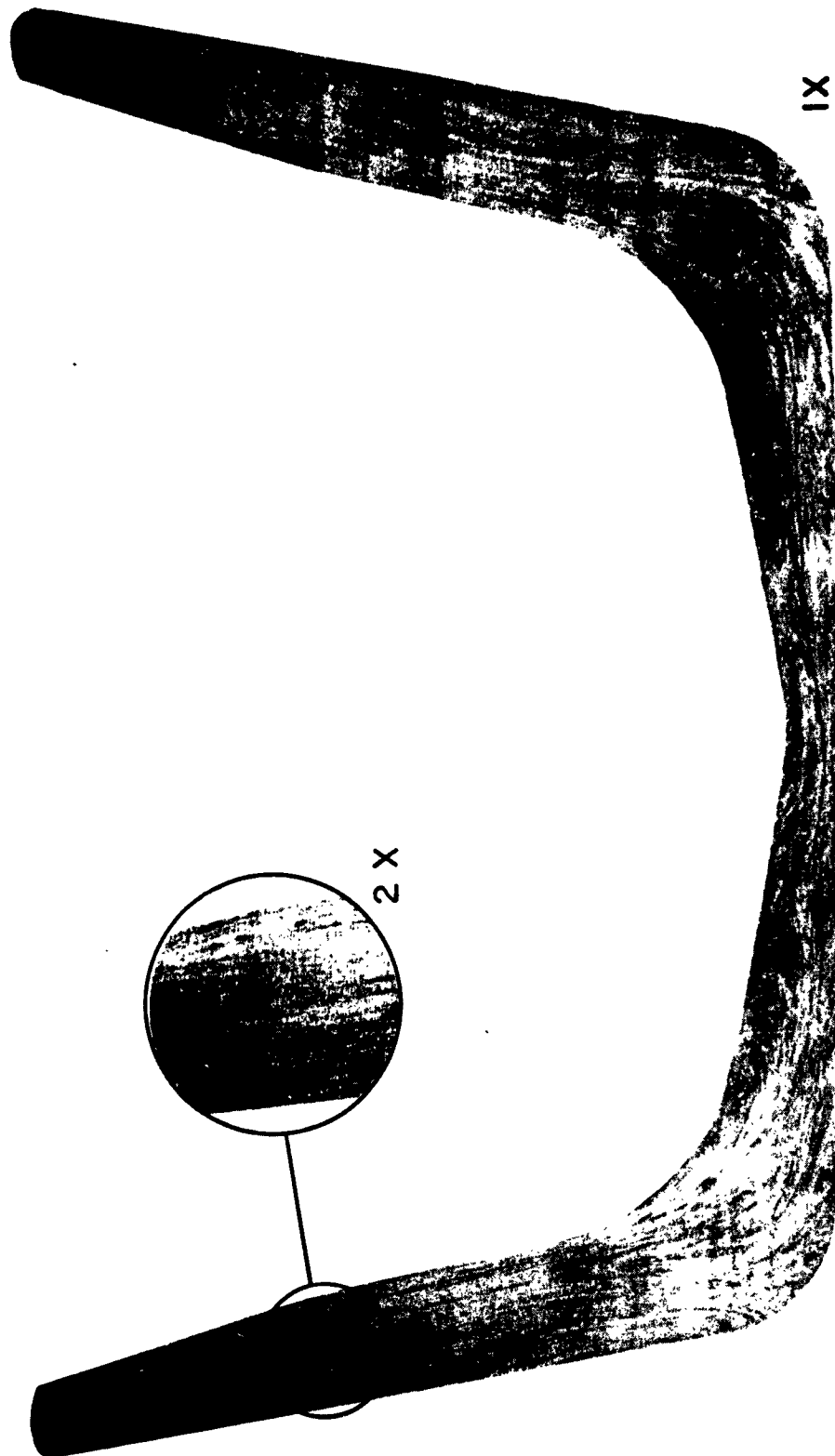
Surface Appearance of the Four Forged Tungsten Billets



Comparative Surface Appearance of Coined Tungsten
Forgings Nos R-1 and S-2



Macrostructure of Coined Tungsten Forging No. R-2



Macrostructure of Coined Tungsten Forging No. S-2



flow patterns; both sections appear to be fully wrought in spite of dissimilar starting structures. A further comparison of the tungsten sections to the coined composite steel section emphasizes the metal flow similarities, i.e., the elongated flow patterns reflect the severity of the work imparted during the back extrusion operations. Analysis of the forging trials and the appearance of the resultant macrostructures produced by the six stage sequence verified the original sequence design concept during scale up. No tooling modifications are required for the remaining forging operations.



V FORGING EVALUATION

A. Yield

The starting weight for the unalloyed tungsten billets was a nominal 50 pounds as compared to an average coined forging weight of 48.1 pounds. As with the reported Phase V forging⁽⁷⁾ the resultant 96.2% forging yield is high. Since the Phase VI sequence retains the original Phase V design concept during scale up, the forging metal losses are similarly incurred solely by in-process surface conditioning and oxidation. Flash pattern scrap was essentially eliminated by the tooling design.

B. Dimensions

The coined forgings were dimensioned at the locations "A", "B", and "C" shown in Figure 2. Position "A" thickness was located at a height of 4-1/4 in. from the cup bottom and was checked at four 90° rotated positions. The dimensions of the six positions checked are recorded in Table II. The data show the dimensional reproducibility achieved. The cup bottom diameter dimensions are within 0.006 in; the greatest deviation from nominal design dimension being 0.008 in. The web sections were reduced below the 0.375 in. design dimension by approximately 0.040 in. and were within 0.013 in. The cup sidewall thicknesses were well within the maximum 0.445 in. dimension targeted for this position. The greatest variation for the "A" dimension was found to be 0.024 in.

To aid in determination of a forging envelope for this part, coined forging S-3 was selected at random, and prepared for concentricity measurements⁽⁷⁾. The measurements were recorded for five I.D. and O.D. height positions at four 90° rotations, as shown in Figure 12. The data are listed in Table III. The outer sidewall concentricity varied by a maximum of 0.006 in. while the greatest inner sidewall concentricity variations were 0.022 in. Based on these results and subsequent surface finish measurements, an adequate forging envelope would consist of approximately 0.010 in. and 0.030 in. on the outer and inner forging walls respectively. The Phase VI forgings showed an 0.008 in. improvement in inner sidewall concentricity as compared to Phase V forgings.

C. Surface Finish

Figures 8 and 9 illustrate the superior forged surface appearance obtained during Phase VI. Sidewall surface roughness measurements for these forgings ranged from 40 to 60 RMS as was reported⁽⁷⁾ for Phase V forgings using identical lubrication practice.

D. Non-Destructive Testing

Super zyglo fluorescent penetrant inspection revealed no additional surface discontinuities other than those described in Section IV-C, Figures 8 and 9. The surface discontinuities found in the coined forgings consisted

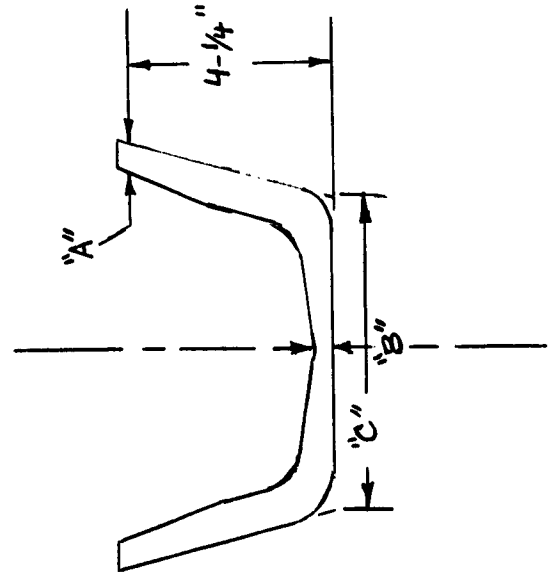
TABLE II

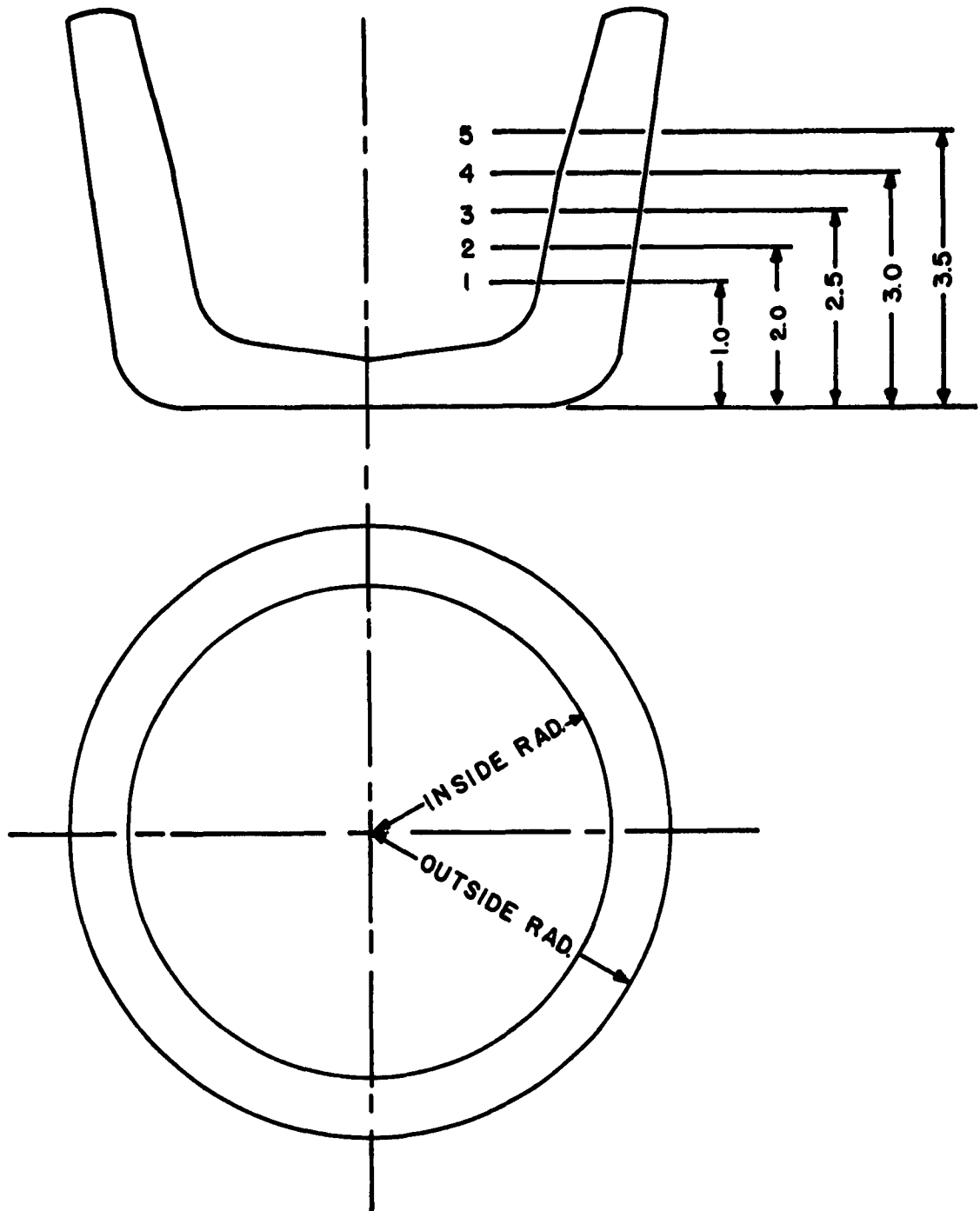
DIMENSIONS OF COINED PHASE VI TUNGSTEN FORGINGS

Forging Billet No.	"A" Dimension (in.) (1)					"B" Thickness (in.)			"C" Bottom Diameter (in.)		
	Design(2)					Design(2)			Design(2)		
	Dimension	0°	90°	180°	270°	Dimension	Measured	Deviation	Dimension	Measured	Deviation
R-1	.445	.421	.438	.440	.419	.375	.325	-.050	6.437	6.432	-.002
R-2	.445	.430	.442	.442	.420	.375	.338	-.037	6.437	6.430	-.007
S-2	.445	.420	.442	.440	.419	.375	.338	-.037	6.437	6.431	-.006
S-3	.445	.422	.440	.440	.418	.375	.336	-.039	6.437	6.429	-.008

(1) Taken at a constant sidewall height of $4-1/4$ in. (see Figure 2).

(2) Nominal design dimension.





Dimensions Taken for Concentricity Measurements of
Coin Forging No. S-3



TABLE III
CONCENTRICITY MEASUREMENTS OF COINED FORGING NO. S-3

Height on Sidewall (in.)	0° Position*		90° Position		180° Position		270° Position	
	I.R.(1)	O.R.(2)	O.R.	I.R.	O.R.	I.R.	O.R.	I.R.
1-1/2	0	0	-.001	+.003	-.003	+.020	-.003	+.021
2	0	0	-.003	+.003	-.004	+.020	-.004	+.020
2-1/2	0	0	-.003	+.002	-.004	+.021	-.003	+.021
3	0	0	-.004	0	-.005	+.021	-.004	+.022
3-1/2	0	0	-.005	-.001	-.006	+.022	-.005	+.022

* 0° position set to 0 at each sidewall height.
(1) O.R. = concentricity deviation of the outer radius.
(2) I.R. = concentricity deviation of the inner radius.
(See Figure 12)



solely of tears in the outer surface cup bottom and radius of forgings S-2 and S-3.

Ultrasonic testing could not be adequately adapted to the inspection of the thin walled inserts as previously discussed⁽⁷⁾. The application of eddy current testing of the tungsten forgings was investigated. The effective test penetration of the tungsten sidewall using a Magna Test unit, Model No. FM 110, was found to be approximately 0.050 in. The obvious limitation of this technique precluded its applicability.

E. Microstructure

To determine the effect of the initial starting billet structure and the forging process on the tungsten work piece microstructure, forgings R-2 and S-2 were sectioned and prepared for metallographic examination. The as-forged microstructures and corresponding DPH hardness values of these sections are shown in Figures 13 and 14.

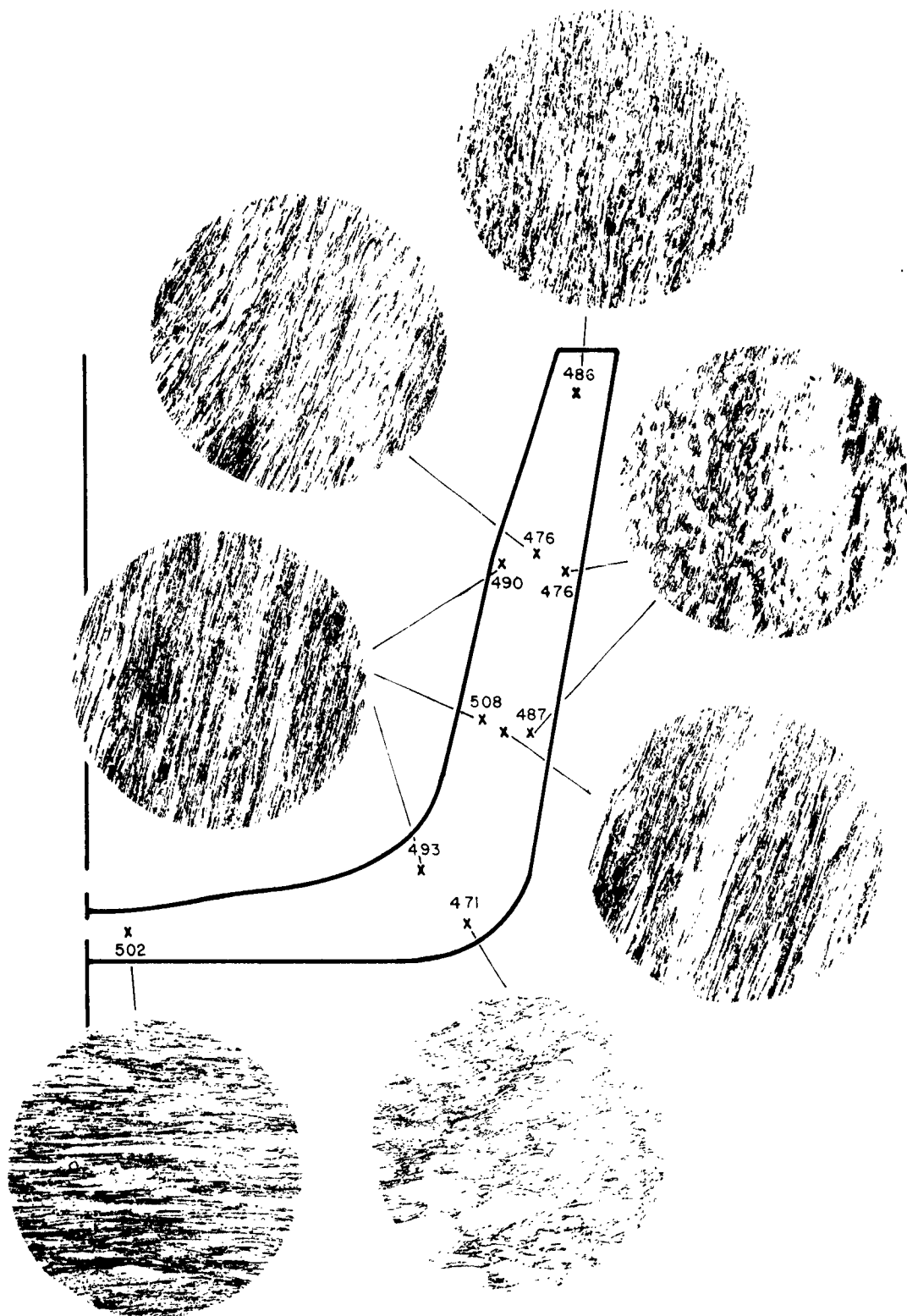
Slightly higher hardness values were recorded for forging S-2. However, both forgings exhibited more uniform hardness values throughout the section than reported for the Phase V forgings⁽⁷⁾. Although no apparent macrostructure differences for forgings R-2 and S-2 could be noted (see Section IV-C), examination of the microstructures clearly indicated the structure desirability of forging R-2. The "R" designated billets forged to the coin configuration showed:

1. Considerably finer grain size;
2. Greater structure uniformity; and
3. More uniformly worked structures.

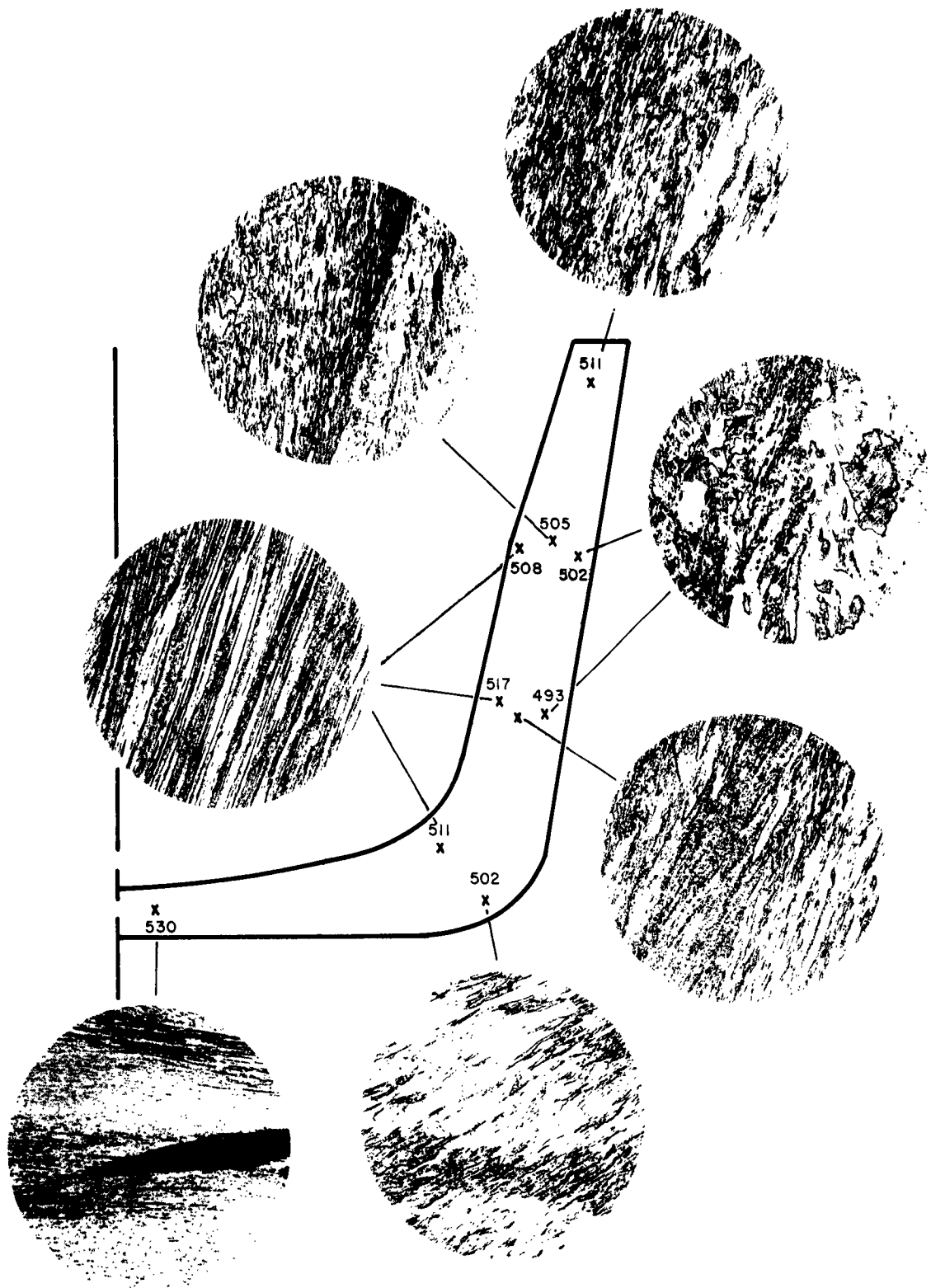
F. Recrystallization

Forgings R-2 and S-2 were further sectioned to provide additional samples to investigate the response of the cold-worked structures to thermal treatment. The recrystallization process was followed in the forging area corresponding to the critical throat section of nozzle inserts. Forging sections were given one hour isochronal heat treatments over the temperature range of 2300°F to 2700°F. The microstructures and hardness data are shown in Figures 15 and 16.

Initiation of the one hour recrystallization in the heavily worked section adjacent to the punch (I.D. throat) was seen to occur as low as 2300°F. The start of recrystallization for the O.D. section occurred at approximately 2400°F. The one hour recrystallization temperature of No. R-2 occurred at 2500°F while No. S-2 was found to be completely recrystallized at 2600°F. The higher recrystallization temperature of forging S-2 can be associated with the coarser grained areas observed in the micro-

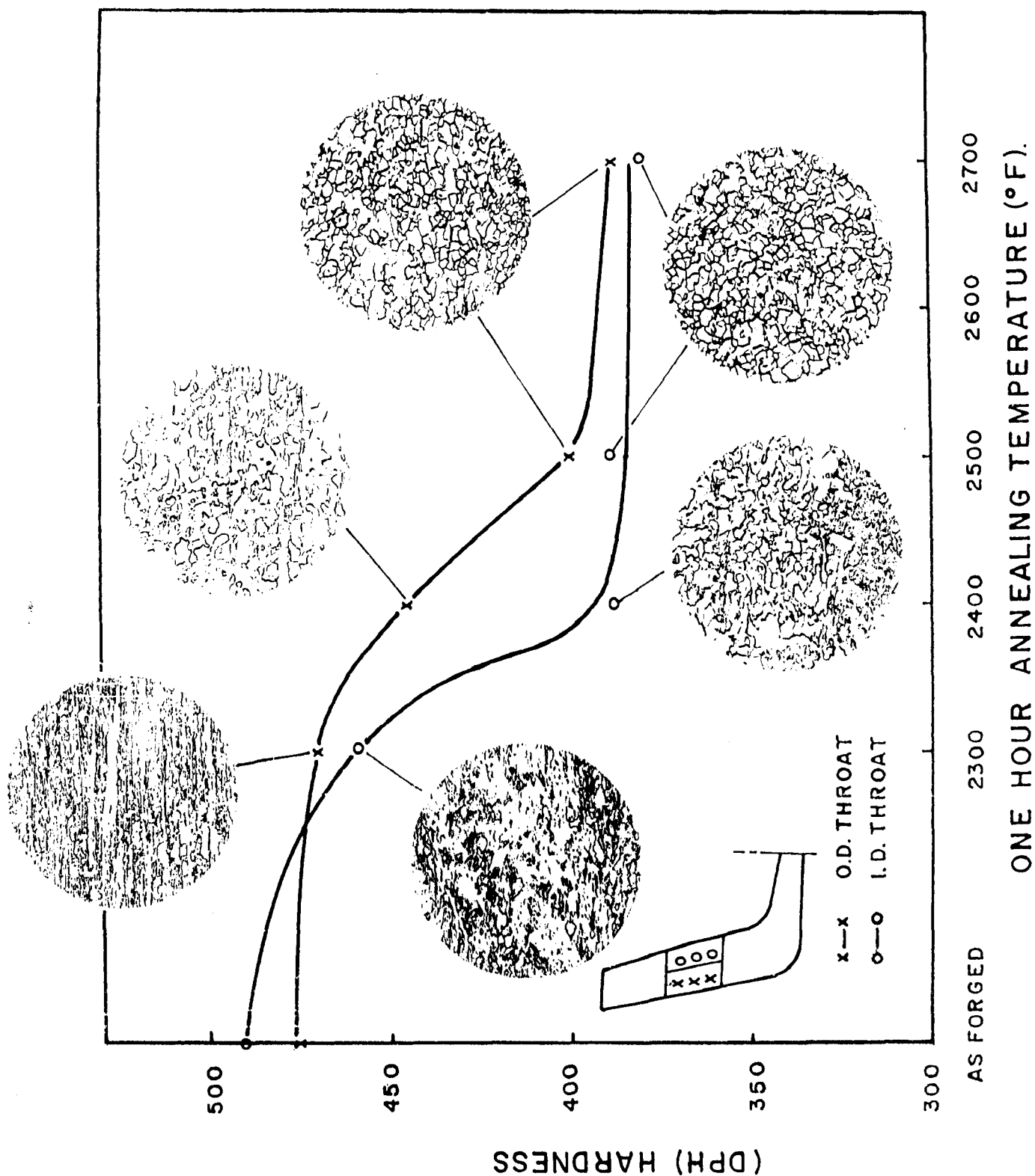


Microstructure As Forged and Diamond Pyramid Hardness for
Coined Forging No. R-2 50X



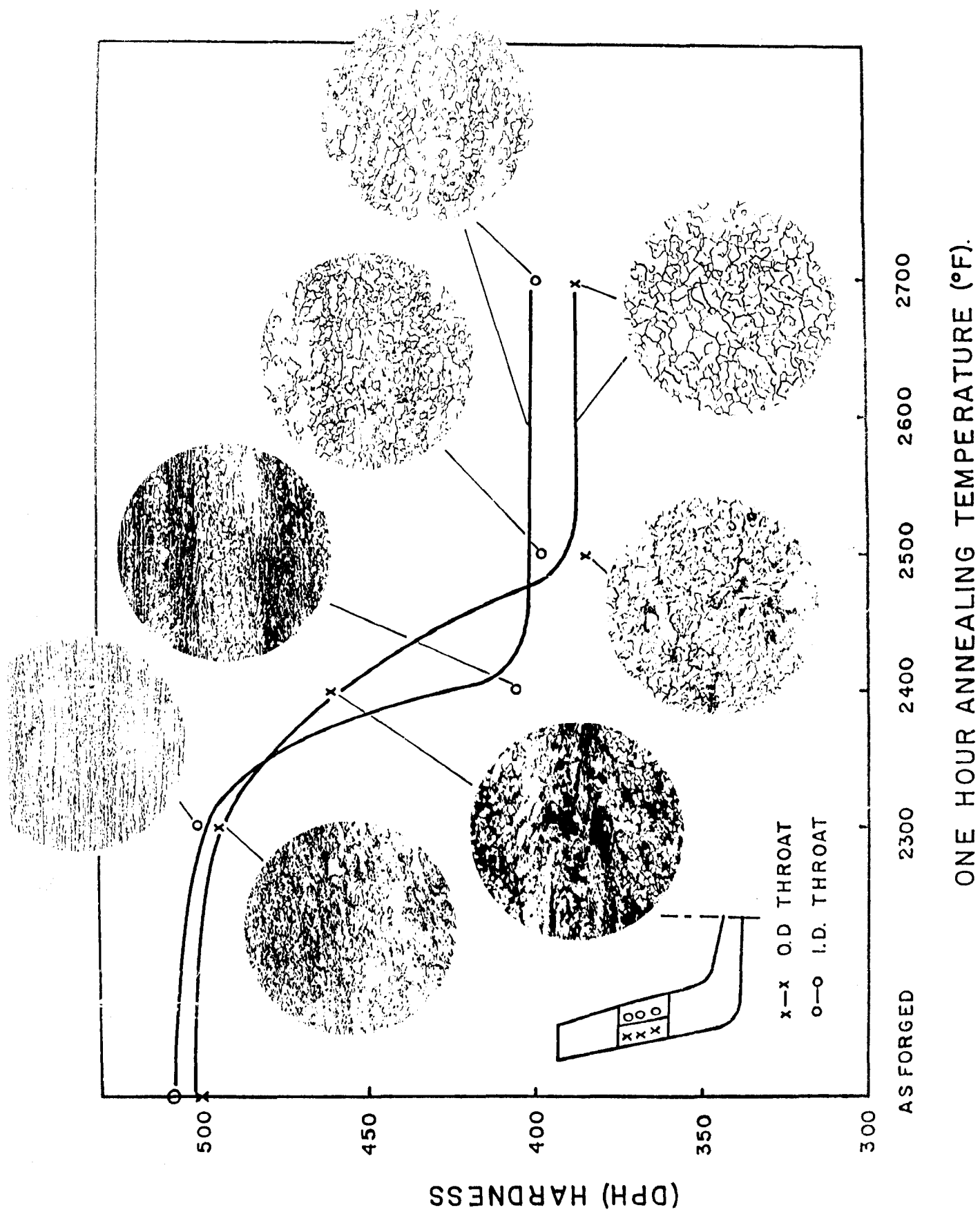
Microstructure As Forged and Diamond Pyramid Hardness for
Coined Forging No. S-2

50X



Recrystallization Behavior of Coined Tungsten Forging No. R-2

50X



Recrystallization Behavior of Coined Tungsten Forging No. S-2

50X



structure. That the start of recrystallization of the Phase VI unalloyed tungsten forgings was observed to occur at approximately 400°F lower than for reported Phase V W-2%Mo forgings(7) can be attributed in part to the following:

1. Finer initial billet grain size;
2. Severe deformation imparted the work piece; and
3. Low reported interstitial levels.

G. Mechanical Properties

Blanks were sectioned from forgings R-2 and S-2, as illustrated in Figure 17, to provide specimens for the determination of mechanical properties. Ductile-brittle transition temperature and elevated temperature tensile properties were determined. The specimen configurations utilized for the testing effort were as previously reported(7).

1. Ductile-Brittle Transition Temperature

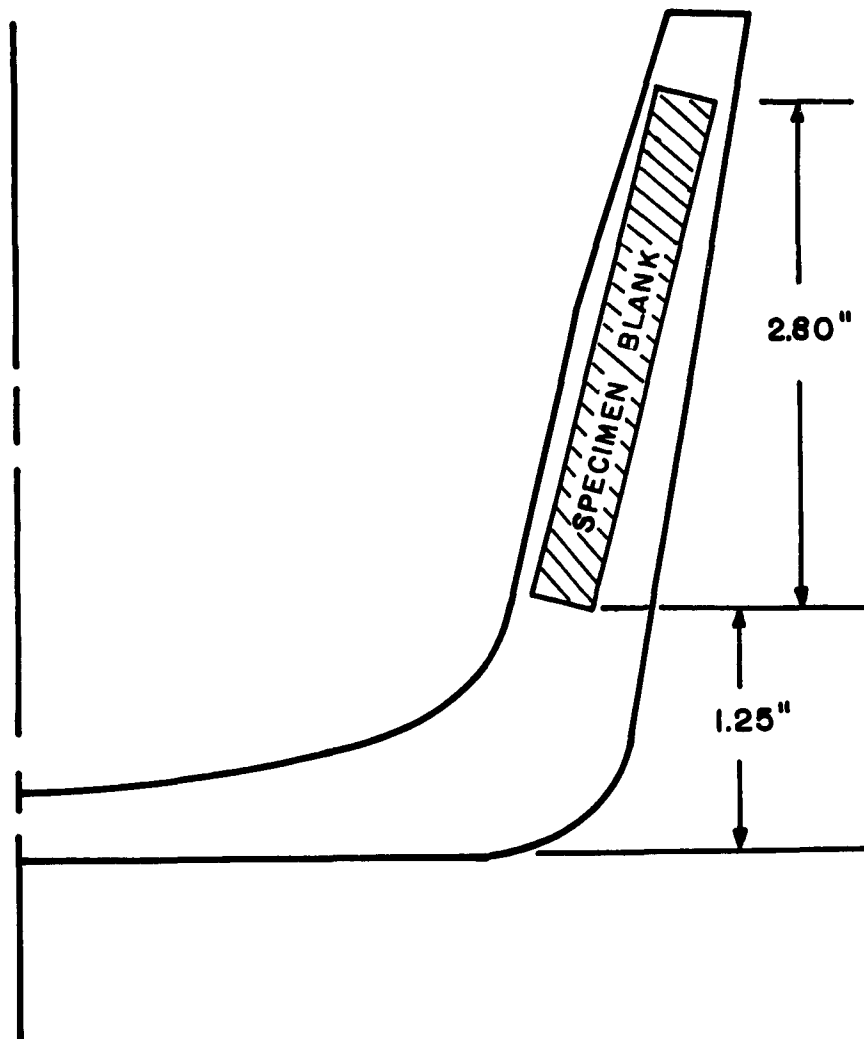
The specimen blanks machined from forgings R-2 and S-2 were centrally positioned within the forging sidewall (Figure 17) to provide properties representative of the worst detectable condition in the forging sidewall. The effect of specimen position in the forging sidewall has been discussed(7). The tensile ductile-brittle transition testing was accomplished on an Instron tensile tester using a constant crosshead speed of 0.020 in./min.

The results of the tensile tests are tabulated in Table IV. Reduction of area and elongation values are plotted for the two forgings in Figure 18. The tensile data indicate the transition temperature of the center section of the sidewall to be 300°F and 325°F for forgings R-2 and S-2 respectively. These ductile-brittle transition temperature values are approximately 100°F lower than reported for the Phase V forgings(7). More significantly, specimen ductility was observed as noted in Table IV at the lowest test temperature (150°F).

2. High Temperature Properties

Test specimens were machined from sidewall blanks of forgings R-2 and S-2. Testing procedures for the radiant heated specimens at 3000°F and 4000°F and the self resistance heated specimens at 5000°F have been outlined(4,7). The results of testing are summarized in Table V.

The strength levels observed over the temperature range tested (3000°F to 5000°F) for the two cast-extruded unalloyed tungsten forgings are comparable to data reported in the Phase I State-of-the-Art Survey



Location of Test Specimens Taken from Forging Sidewall

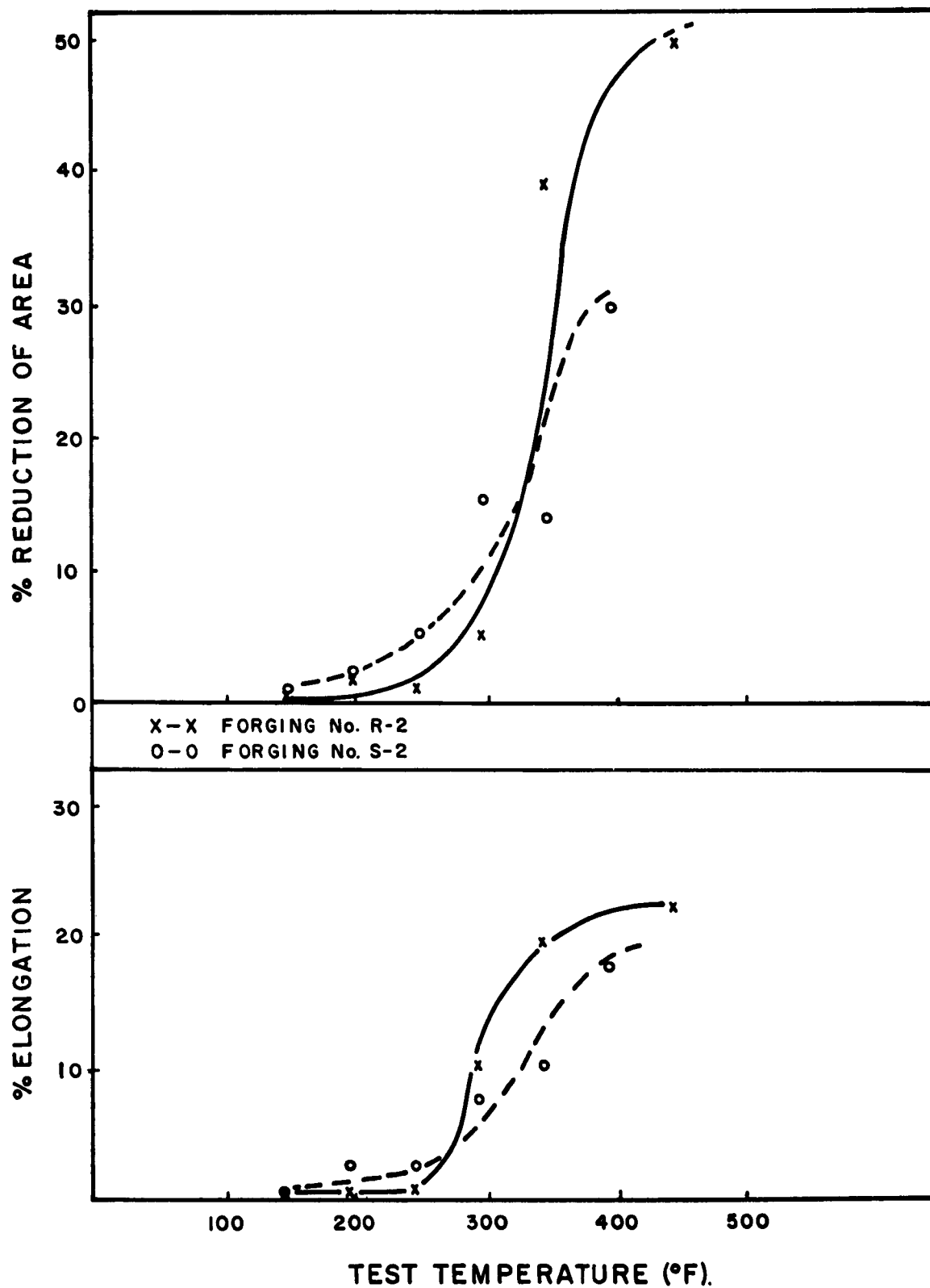


TABLE IV
TENSILE TEST DATA FOR PHASE VI THIN SECTION FORGINGS*

<u>Test Temp. °F</u>	<u>0.2% Y.S. (psi)</u>	<u>U.T.S. (psi)</u>	<u>% R.A.</u>	<u>% Elongation</u>
<u>Coin Forging No. (S-2)</u>				
150	180,300	180,300	1.3	1.3
200	167,500	167,700	2.5	3.1
250	146,000	146,000	6.3	2.8
300	146,300	147,300	16.2	7.2
350	136,700	137,500	13.2	10.0
400	119,300	119,300	30.4	17.9
<u>Coin Forging No. (R-2)</u>				
150	173,900	175,000	1.0	0.9
200	163,800	166,400	1.9	1.4
250	149,100	152,000	1.2	1.2
300	141,000	144,400	5.1	10.5
350	130,000	132,900	36.8	19.4
450	110,200	114,600	50.5	21.7

* Tests were conducted using a constant crosshead speed of .020"/min.

Note: Specimens were tested in the as-forged condition. Specimens were machined from forging sidewall blanks as shown in Figure 17.



Tensile Ductile-Brittle Transition Properties of
Coined Tungsten Forging Nos. R-2 and S-2



TABLE V
HIGH TEMPERATURE TENSILE PROPERTIES OF PHASE VI
THIN SECTION TUNGSTEN FORGINGS*

<u>Test Temp. °F</u>	<u>0.2% Y.S. (psi)</u>	<u>U.T.S. (psi)</u>	<u>% R. A.</u>	<u>% Elongation</u>
<u>Coin Forging No. (S-2)</u>				
5000	3,400	5,000	-	-
4000	4,000	7,200	98	100.6
3500	5,500	10,400	98	64.2
3000	8,400	15,800	98	69.0
<u>Coin Forging No. (R-2)</u>				
5000	4,200	4,800	-	-
4000	3,400	6,400	98	67.6
3500	6,000	11,500	96	77.8
3000	7,300	16,200	85.5	66.0

* Tests were conducted using a constant crosshead speed of .020"/min.

Note: Specimens were tested in the as-forged condition. Specimens were machined from forging sidewall blanks as shown in Figure 17.



for extruded and swaged arc cast unalloyed tungsten⁽¹⁾. A comparison of the high temperature tensile properties of previously tested W-Mo alloys to the unalloyed tungsten forgings shows significantly higher strengths prevail for the W-Mo alloys below 4000°F^(4,7). At 4000°F comparable strength levels are observed. Above 4000°F the solid solution strengthening effect of molybdenum is lost and the unalloyed tungsten exhibits greater tensile strengths.

H. Analysis of Forging Tooling

The punch and die inserts used during Phase VI are shown in Figure 19. The tooling was machined from AISI type H-12 tool steel and hardened to R_c 50-52. Rapid billet transfers enabled the use of conventional tooling materials and tooling lubricants in spite of forging temperatures of 2350°F. A post forging visual inspection of the tooling as well as the dimensional consistency of the coined forgings indicated no perceptable tooling wear. Since only four forgings were produced, estimates of tooling life are currently precluded.



(A) Usetting Punches



(B) Back Extrusion Punches



(C) Dies

Scale 0.1X

Punch and Die Inserts Used During Forging Trials



VI CONCLUSIONS

The forging process developed for the Phase V universal thin section forging has been successfully scaled up. The following conclusions can be drawn from the forgeability and property evaluations of the scaled up tungsten configuration:

1. The in-process controls developed and forging parameters established during Phase V have been verified as adequate to control the scaled up Phase VI tungsten forging process. The results show:
 - a. Excellent as forged surfaces,
 - b. The optimum forging temperature range developed for Phase V (2350°F to 2200°F) is applicable to the scaled up forging, and
 - c. Dimensional consistency can be controlled during scale up.
2. Unalloyed tungsten of fine grained fully recrystallized structures as compared to billets of initially hot-cold worked structures has been shown the former to possess:
 - a. Better forgeability, and
 - b. More uniform as forged microstructures.
3. Low ductile-brittle transition temperatures observed for the coined tungsten forgings verify the original design concept for production of thin wall insert configurations and further emphasize the severity of the deformation imparted by the forging process.



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VIII PROGRAM FOR THE NEXT PERIOD

During the next reporting period the Phase VI program will be completed. This will include:

1. Procurement of eight additional cast-extruded tungsten billets with a fully recrystallized microstructure.
2. Forging of the eight tungsten billets.
3. Forging and property evaluation of the parts produced to demonstrate the reproducibility of the process.



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The forging process developed
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successfully scaled up. Initial forging trials of the scaled up configuration have been completed with high purity cast extruded unalloyed tungsten billets having hot-cold worked and recrystallized structures. Test data indicate the superiority of starting billets of uniformly recrystallized structures. Evaluation of forgings produced demonstrates that forging quality can be controlled during scale up. Ductile-brittle transition temperature and high temperature tensile properties are reported.

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